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Georgia Institute of Technology

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ABSTRACT

The design of hypersonic vehicles is influenced by tightly coupled interactions between aerodynamics, propulsion, and structures. Therefore, in the conceptual design phases, the identification and mitigation of potential problem areas and disciplinary interrelations are critical. Although the multidisciplinary character of hypersonic designs is well known, research in hypersonics is primarily focused on the isolated disciplines with side notes on the interactions. The designer has to integrate all the disciplinary information and create a successful system. This integration is a tedious and elaborate process involving time-consuming iterations.

This paper proposes a new approach and entails the creation of Response Surface Equations from the various constituent disciplines considered. This method allows to quickly assess the implication of design decisions at the top level using the multiple disciplinary meta-models. As an exercise, the paper demonstrates the generation of a structural meta-model for a hypersonic strike fighter that must fulfill certain mission requirements.

MOTIVATION

The design of hypersonic vehicles has recently received an increase in attention. The necessity for such a vehicle proved itself repeatedly in raids in the Mid-East during Desert Storm and former Yugoslavia. These conflicts sparked the research in a vehicle that could eliminate time critical targets (TCT). TCT encompass missile launchers and mobile artillery; targets that are in a fixed location for only a brief time, e.g. Scuds, SAM launchers. In addition, many of the current precision strike weapons (e.g. Tomahawk, CALCM) are reaching their useful life and use outdated technology which increases detection and reduces effectiveness. To counter those time critical, high value targets, various institutions expressed interest in the feasibility and affordability of an air vehicle that can cruise at hypersonic speeds. The current investigation focuses on the structural requirements of such a new quick response, highly survivable, all weather, around the clock, strike system. It is note worthy to also mention Graham **[1]**, Hollingsworth **[2]**, and McDonald **[3]** which discuss requirements and methodology for other design areas of hypersonic vehicles.

The added complication of the design of hypersonic vehicles creates a number of interactions that are usually not accounted and addressed in conventional subsonic or supersonic designs. The most important ones being thermal loads and stresses, thermal protection system (TPS), and aeroelastic considerations. The paper emphasizes the need and the creation of meta-models for the vehicle structure, making use of a rubberized finite element model (FEM). Ideally, these models allow for technology infusion, such as exotic materials, different TPS, etc. The goal, from a designer perspective, is a highly integrated, physics-based, computational environment, requiring minimal input and permitting multiple, fast design iterations.

OBJECTIVES OF RESEARCH

Typically, hypersonic vehicles have an unusual shape, unusual structures, unconventional materials, and additional system requirements (thermal protection of structure and avionics, flight control laws at low and high speed, etc.). Research in the hypersonic area has focused on the individual disciplines itself: aerodynamics, structures, materials, propulsion, etc. It is important to realize that such a design has limited or no historical database to rely on. In addition, the designer (using public domain information) has very little relevant up-to-date research in hypersonic *systems* to his/her disposition. Lastly, the disciplinary interactions are so strongly coupled that the design group would have to re-iterate the design in a classical approach until all requirements are satisfied, leading to a point design. Optimization of this point design would then be possible, however recognizing that this might not be the most optimal design, is important. Hence, designing such a system would prove to be cumbersome with a classical engineering approach and the optimality of the result would be in doubt.

When reviewing the mission requirements for a new system, it is still unclear what the vehicle that will fulfill that mission will look like. Thus as aforementioned, it is necessary for the designer to have a parametric model of the airplane to allow for quick changes in the shape and size of the vehicle. Any finite element or structural code can be used as long as the specific response can be determined with that code. Typically, for the structures of a vehicle, this would encompass the weight for individual structural components or the total airplane. In this paper, a model was created to run with the Automated Structural Optimization System (ASTROS) **[4]** finite element package. Further, the paper clarifies how a program was written to efficiently and quickly make a finite element model input file.

However, this still required the designer to execute an FEM code, which still resulted in time-consuming iterations. To prevent the long and arduous iterations and design a successful system, Response Surface Equations (RSE) were generated for the structural weight and could possibly be tied together with other disciplines in a higher level synthesis and sizing tool. The equations describing various responses required by the synthesis and sizing tool (one equation describes one response) were called meta-models.

To achieve this synergistic design environment, the authors designed a program that used geometrical information and created that parametric structural model. This model was the rubberized finite element model allowing the use of a Response Surface Methodology (RSM) **[5]**. This RSM permitted multiple, fast iterations whereas in traditional design, these iterations would typically be computationally intense.

IMPLEMENTATION

First, the finite element code used will be discussed followed by the exposition of the methodology and the shell script that generated the ASTROS input file.

ASTROS

For the structural analysis of the vehicle to be designed, the finite element code ASTROS was chosen for the reasons summarized below. For a complete list of capabilities, reference is made to the ASTROS user's manual **[4]**.

- Static analysis for any structure under any loading condition can be performed.
- Dynamical analysis for any structure under any loading condition, including flutter and divergence (two of the many topics to be covered in depth when designing hypersonic vehicles).
- Temperature effects, especially with hypersonic vehicles having severe kinetic heating, needed to be addressed. ASTROS allowed investigating this by specifying temperature gradients and indicating associated stress concentrations in the structure due to the heating.
- An important feature of ASTROS was the integrated optimization routine. The analyzed structure could be optimized and designed for any given constraint, i.e. stresses due to temperature, flutter and divergence limits, and maximum deflections.

The use of ASTROS required very few assumptions to be made in contrast with other simplified structural analysis codes such as ELAPS **[6]**. There were no first order approximations, such as equivalent plate thickness, scaling factors, or simplified beam theories. This level of accuracy was not needed in conceptual design. Nonetheless, ASTROS was chosen as it was a complete tool and could be used throughout the whole design cycle preventing time or data loss due to switching codes.

RESPONSE SURFACE METHODOLOGY

To overcome the disciplinary integration problem previously mentioned and commonly found with revolutionary, unconventional concepts where interactions between disciplines were usually unknown, a response surface methodology approach was used. This method has been used for a multitude of different problems and has proven its abilities to handle complex systems during design studies for a High Speed Civil Transport (HSCT) **[7]** and Supersonic Business Jet (SSBJ) **[8]**.

The methodology uses a Design of Experiments (DoE) to perform a screening test on all the variables that were thought to contribute to the variability of a specific response. This two-level screening test and was designed to find which variables were contributing the most to the variation of the response. The experiments were run with ASTROS and analyzed using a statistical analysis program, JMP **[9]**. The most important contributing variables were identified via a analysis of variance (ANOVA). Subsequently a three-level DoE was constructed with only the screened, most influential variables. All cases were again run using ASTROS. From this three-level DoE, the statistical program calculated the coefficients for an RSE of the following polynomial form:

$$R = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} b_{ij} x_i x_j$$

where: R was the fitted response, b_i represented the regression coefficients for the linear terms, b_{ii} the quadratic coefficients, b_{ij} the cross-product coefficients or second order interactions, x_i and x_j the design variables, and $x_i x_j$ denoted interactions between two design variables.

After the RSE was generated, distributions could be assigned to each variable (e.g. number of spars and ribs in the wings can vary uniformly between 2 and 6). This could be accomplished with the probabilistic program Crystal Ball **[10]**. A Monte Carlo Simulation (MCS) was run with the RSE, distribution and ranges for the variables in that equation. The output from the MCS were cumulative probability distributions, which indicated what percentage of all possible systems was within, below, or above a certain weight limit. Thus, a measure of the probability that the system would meet a weight goal given the current problem setup. The whole process is clarified in *Figure 1*.

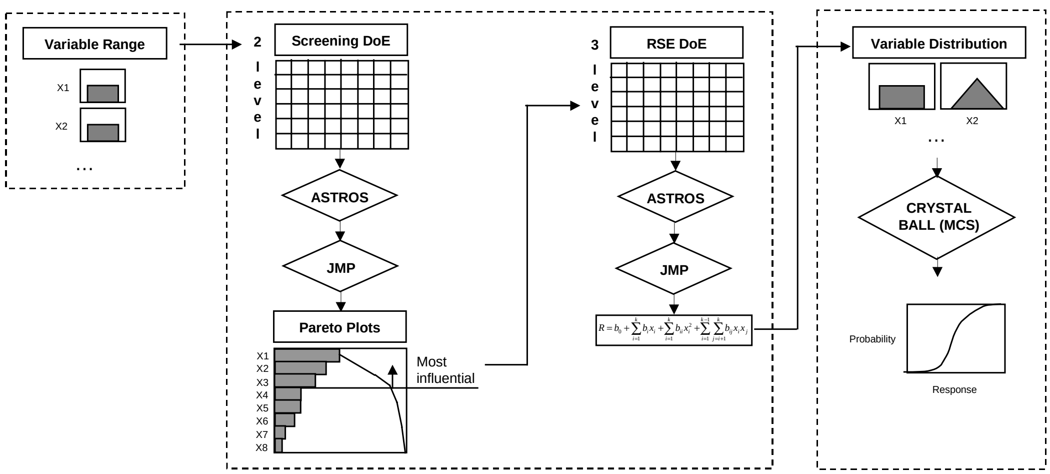

Figure 1: Response Surface Methodology for Parametric Hypersonic Vehicle

ASTROS AUTOMATED INPUT FILE GENERATION

To take full advantage of ASTROS' capabilities and to be able to run the DoE, an automatic input file generation was necessary. This was accomplished by writing an external shell script that generated the loads, boundary conditions, and structural elements from data that was generated by the other disciplines. The input and output to various disciplines is illustrated in *Table 1*.

To begin the process, the external geometry from the aerodynamic input file was needed. From there, internal grid points were created using designer input. This input consisted of number of ribs and spars in the wing, number of bulkheads and frames in the fuselage, etc. Next, structural elements were attached to the newly created gridpoints in the following manner: the skins were modeled with membranes, the internal structure was made of shell elements, and each node was connected with rods.

When the structure was defined, the different loads were generated and distributed according to predefined rules. The different loads included payload weight, fuel weight, propulsion unit weight,

Table 1 Disciplinary Interrelations

Discipline	Input	Output
Propulsion	Dimensions Weight Pressures Fuel Consumption	
Aerodynamic Stability & Control	Loads Geometry	Weight Update
Sizing & Synthesis	Technology Infusion	Weight & CG RSEs
Economics		Weight RSEs

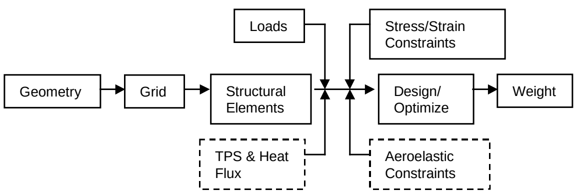

Figure 2: Automated Input File Generation Overview

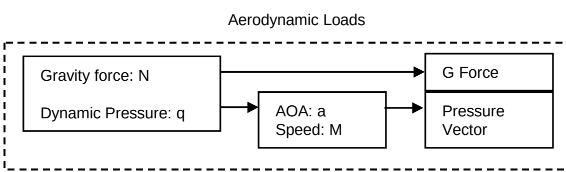

Figure 3: Aerodynamic Load Routine

exhaust pressures on the structure, and aerodynamic loads. The fuel would be distributed in a certain area inside the fuselage, as were payload and propulsion unit weight.

The aerodynamic loads were generated via another routine. From the aerodynamics output file, when a specific load factor (N) and dynamic pressure (q) were specified the routine could find the pressure distribution on the vehicle from the output file using an angle of attack and Mach number. This pressure distribution was then modeled on the structure and all previously defined weights were updated to account for the inertia relief, i.e. the g-force.

Afterwards, the rest of the input file was generated: stress and strain constraints were specified for the chosen material of the structure. Alternatively a temperature gradient could be specified at specific points and, if desired, aeroelastic constraints could be added. After the load generation, the assignment of boundary conditions had to be completed. Assumptions were made that were specific to the vehicle considered. More details on this follow in the example discussion. Also, after defining constraints, design variables needed to be identified and will be discussed in the next section.

A basic outline of the main program is illustrated in *Figure 2*. The aerodynamic load routine in *Figure 3*.

The shell script would be vehicle-specific and dependent on the 'type' or 'family' of vehicles considered. An axi-symmetric vehicle would have payload and weights distributed differently than a waverider configuration. In addition, the boundary conditions and design variables would be different. The up-front time was increased to automate the process, however, the timesaving and information obtained as the design configuration was changed was valuable to the designer.

APPLICATION

The above methodology was applied to a Request for Proposal (RFP) for a Hypersonic Strike Fighter (HSF) **[11]**. The RFP asked specifically to look into the feasibility of such a system given certain mission requirements. The following is an excerpt from that RFP.

> *"In future military operations the reaction times of threats are expected to make it more difficult to target and destroy "time critical high value" targets than it is in today's military operations. This concept study is to address the feasibility and the affordability of an air vehicle that can cruise at hypersonic speed, employ advanced high speed air-to-surface and air-to-air weapons as well as current munitions to provide a very quick reaction capability against any potential aggressors. These aircraft are expected to be deployed to military airbases or on aircraft carriers that must be located at a relatively "safe" distance from theater ballistic missile threats that are expected to be available to an increasing number of countries in the 2015 and beyond time period."*

The nature of the automated input file generation required splitting the problem into classes of vehicles for the following reason: a waverider had a different geometry definition when compared to the axi-symmetric vehicle. Also, the internal distribution of loads was different as were boundary conditions and design variable groups. Hence, three different families of vehicles were identified that could possibly fulfill the mission successfully. These three classes were waverider configurations, axi-symmetric configurations, and HyperX-like configurations. Each family would have a specific program to generate the input file. This paper will concentrate on the Hyper-X-class family.

Also part of the RFP was a general design requirement table with threshold and desired values, as listed in *Table 2*.

Table 2 General Design Requirements for HSF

Performance/Attribute	Treshold	Desired
Cruise Speed	Mach 4	Mach 8
Max Speed at SL	400 Kts	630 Kts
Mission Radius	750 NM	1500 NM
Design Payload	2 Advanced High Speed Weapons	8 Advanced High Speed Weapons
Alternate Weapon 1	2 JASSMs or SLAM-ERs	8 JASSMs or SLAM-ERs
Alternate Weapon 2	2 AAMs	8 AAMs
Struct. Design Load Factor	3 G's	5 G's
Combat Turnaround Time	Less than 6 hrs.	Less than 2 hrs.
Avionics	NAVCOM & ID	CNI + Radar MTI & Spot Modes + EW
Takeoff & Landing	8000 ft Runway Std. Day, SL	Carrier suitable
TPS	Must be addressed	

HYPER-X

The Hyper-X-class of vehicles was the first family of designs investigated for a couple of reasons. NASA initiated a couple of research efforts in these vehicles in the recent past. The two vehicles investigated (NASP and Hyper-X, *Figure 4* and *5*) both had similar configuration. The authors decided this would be a good starting point.

An outside geometry was created, *Figure 6*. In the figure, the origin for the coordinate system is specified at the nose on the center line. The whole geometry was defined with 20 gridpoints. This constituted the starting point for the structural input file. Note that the wings are not shown in the figure. The wing itself is defined by another eight points and had a diamond shape as a first approximation by the aerodynamic program.

The first part of the program was the creation of the internal gridpoints. In a first iteration, it was decided that splitting the vehicle up in four sections was the most straightforward solution to create the internal structure. There would be a nose, inlet ramp, propulsion/engine, and exhaust segment, *Figure 6*. For each section, three variables were assigned: the number of sections in the X, Y, and Z direction. This in turn allowed a simple routine to calculate all the gridpoints that were additional to the four of gridpoints needed to specify one segment. Some of these new, additional gridpoints are shown in *Figure 7*.

After the additional gridpoints were made, the structural elements were attached as mentioned before. For the Hyper-X, this result is shown in *Figure 8*. The vertical shade illustrates membrane elements for the skins, the horizontal shade is for the shell elements. All gridpoints were connected with rod elements that lay along the edges of the

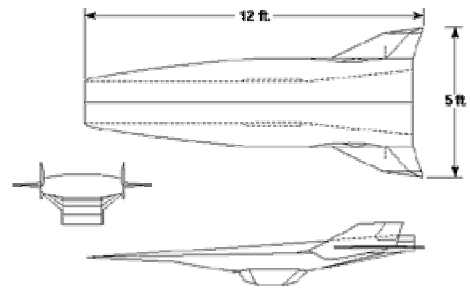

Figure 4: NASA Hyper-X Research Vehicle

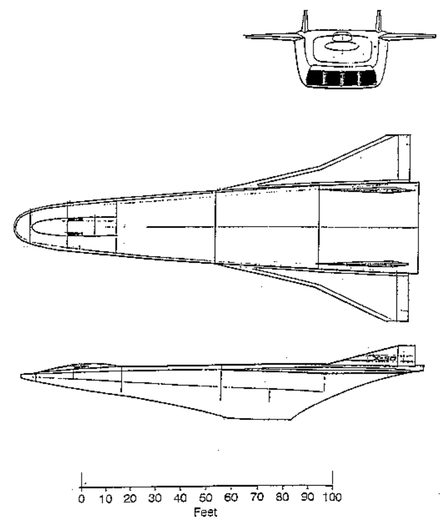

Figure 5: X-30 NASP Research Vehicle

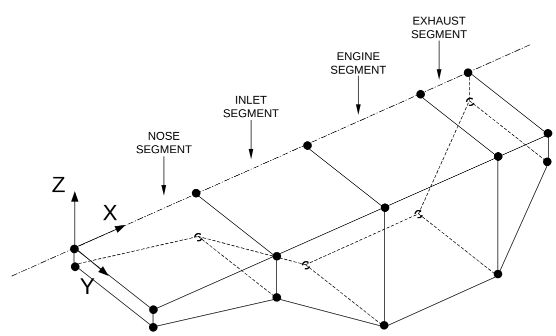

Figure 6: HyperX Geometry

generated by the program. For the purpose of this paper, these structural variables just summarized with rod elements that lay along the edges of the two types of panel elements. Using these three variables per segment, different levels of structural density could be generated if the airplane needed more structure. Also more importantly, the effect on weight could be tracked. *Figure 9* shows an example of the different levels of structural density were fixed, thus allowing focus on the main effect of scaling the vehicle.

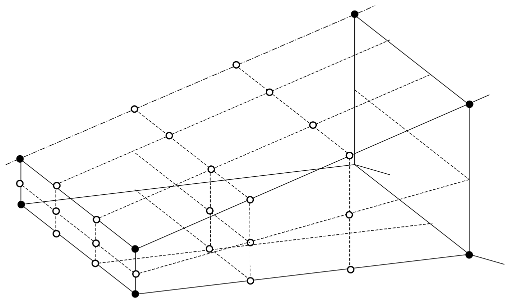

Figure 7: Internal Structure – Gridpoints

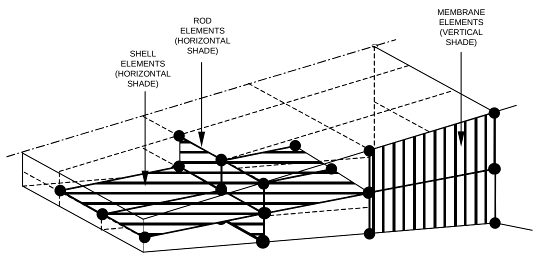

Figure 8: Internal Structure - Elements

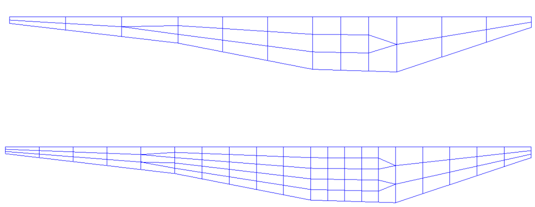

Figure 9: Structural Level of Density

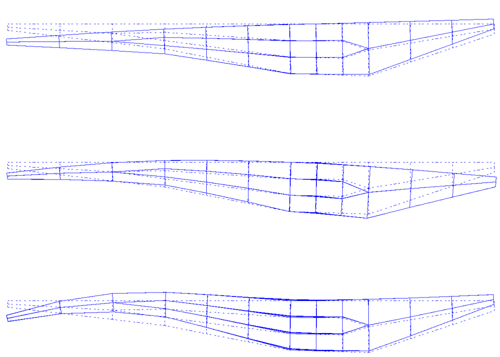

Figure 10: First Three Bending Modes

Boundary conditions were generated accordingly and the plane of symmetry of the vehicle was restrained in the Y direction. A box of four nodes was restrained in the X and Z directions. These four nodes were located in the engine segment, as the center of gravity would most likely be positioned in that segment. A modal analysis was performed as a check for the correctness and validity of this assumption. Some results of the first three bending modes are illustrated in *Figure 10*.

As mentioned before, three design variables per segment existed: the thickness of the shell elements, the thickness of the membrane elements, and the area of the rods. This gave twelve (three times four segments) design variable lists in ASTROS.

As stated, the internal geometry variables were frozen. Only the external geometry would be varied and the following variables were chosen:

- length of the nose segment (L1),
- length of inlet segment (L2),
- length of engine segment (L3),
- height of the nose segment (H1),
- height of inlet segment (H2),
- height of engine segment (H3),
- width of the vehicle (W), and
- scaling factor of the length of the vehicle (SC).

This choice of variables was based on the following assumptions: the original length of the vehicle was 75ft. The vehicle had a constant width, the length of the exhaust segment was the total length minus all the other segments and multiplied by the scaling factor. Also the height in the engine segment was constant and the height at the end of the vehicle was the same as the front end. The following table illustrated the ranges of the eight variables.

Also note that the vehicle was considered without wings and other aerodynamic surfaces. An extract from the full DoE table is shown in *Table 3* and *4*, where a –1 symbolized that variable at the minimal setting, a +1 at the maximal value and 0 in the middle of the variable range.

<u>Results</u>

The different input files were generated and run with ASTROS utilizing its optimization routine. The converged weight output of the fuselage using

Table 3 DoE Variable Ranges

CASE	L1	L2	L3	H1	H2	H3	W	SC
	% of L	% of L	% of L	% of L	% of L	% of L	% of L	
MIN	15	15	20	2	8	14	5	0.7
MID	17.5	17.5	22.5	4	10	17	7.5	0.85
MAX	20	20	25	6	12	20	10	1

Table 4 DoE Case Setup

CASE	L1	L2	L3	H1	H2	H3	W	SC
1	-1	1	1	-1	-1	1	1	-1
2	-1	-1	-1	1	1	1	1	-1
3	1	-1	-1	1	1	-1	-1	1
4	1	-1	1	1	-1	1	-1	-1
5	...	...						

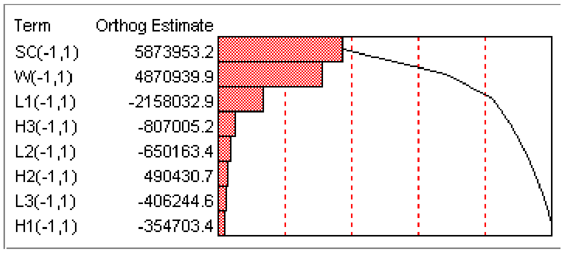

Figure 11: ANOVA, Pareto Analysis

ASTROS was entered in JMP and an analysis of variance (ANOVA) was performed on the weight results. The outcome of this ANOVA are depicted in the Pareto analysis chart in *Figure 11* illustrating which variables in the external geometry influenced the variance of the weight the most.

Important to note is that ASTROS over estimated the weight. The reason for this can be found in two distinct aspects of FEM:

- FEM from the outset was meant to calculate stresses and strains and to optimize structures. The code was never meant to determine weights of vehicles very accurately, which is what is attempted here.
- The correctness of a weight of a structure is directly proportional to how correct the structure is modeled. The assumptions made during the modeling of the structure helped to keep the problem manageable. This however led to a structure that was over-simplified, only discovered in the later stages.

The solution to the too high weight prediction of the FEM was to calibrate an example with weight equations from Raymer **[12]**, adjusting them for this type of vehicle. The authors note that there were interesting developments in the domain of weight estimation at the conceptual level, notably the work from Komarov and Weisshaar **[13]**.

Eventually, the following parameters were chosen to contribute to the variation of the response:

- length of the nose segment (L1),
- height of engine segment (H3),
- width of the vehicle (W), and
- scaling factor of the length of the vehicle (SC).

With these four variables a new three-level DoE was constructed and the cases were again run with ASTROS. After this was done and the weight output was entered in JMP, the final RSE was generated. Note that in order to generate successfully a meta-model for the weight, the problem had to be split in two RSEs. The single RSE for the entire design space predicted negative weights at certain settings of the variables. The reason for this behavior is found in the wide scatter of the data points and only fitted a quadratic to this problem.

The solution to having to split up the problem lies in three solutions.

- Increasing the number of data points by going from a 3-level o a 5-level RSE, increasing the number of data points to fit a surface.
- Another possibility would be to do a full factorial analysis to achieve a better fit, giving the same result as the 5-level RSE.
- The best solution but also the hardest one lies in the creation of 16 RSEs that cover the entire space. Because each of the variables had a minimum and a maximum, this gave 16 different combinations of minimum and maximum.

For brevity, this paper only discussed one RSE, the one where all the variables were in the high range. The prediction profiles for this equation are depicted together with the contour profile of the RSE (*Figure 12* and *13*). The first item depicts how the weight is influenced by a change in one of the variables. As can be seen from those graphs, the relationship between L1 and H3 is non-linear, the other two are almost linear relationships. Using the RSM, it was easy to move the hairlines for the variables and immediately the RSE displayed the resulting weight. Every move of the hairline would correspond to running a case in ASTROS. The time saving over setting up and running ASTROS was obvious.

More importantly however, the contour profiler allows the user to assess the sensitivity of boundaries and visualizing the effect of how fast a variable change affects the design space. In *Figure 13*, the white space is the available design space. The intersection of the two black crosshairs was the chosen design point. Also plotted are three different constraints for maximum weight: 10,000, 13,000, and 16,000 lbs. airframe weight. The effect

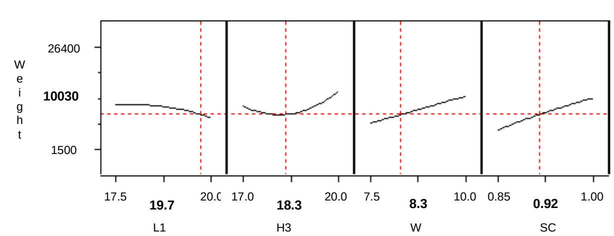

Figure 12: Prediction Profiles for Weight

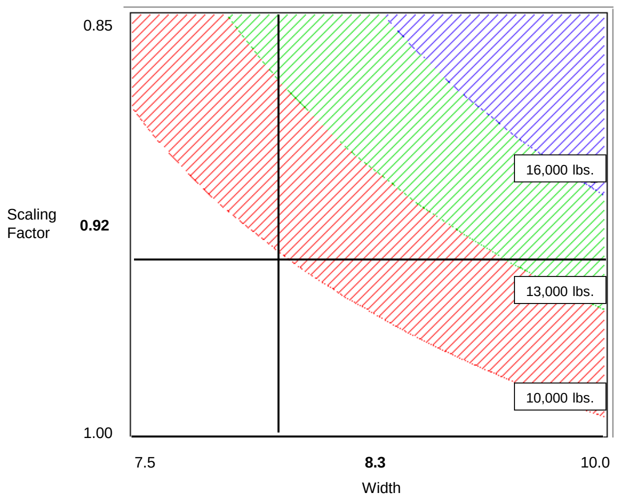

Figure 13: Contour Profile with Weight Constraints

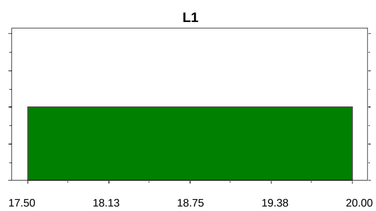

Figure 14: Segment Length (L1) Variable Distributions

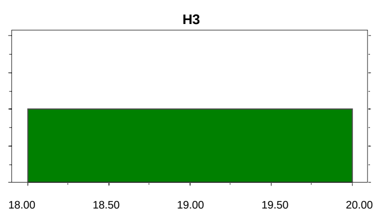

Figure 15: Segment Height (H3) Variable Distributions

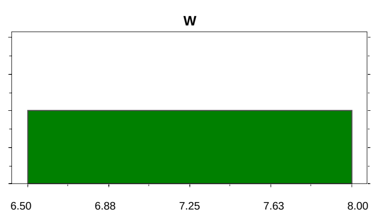

Figure 16: Width (W) Variable Distributions

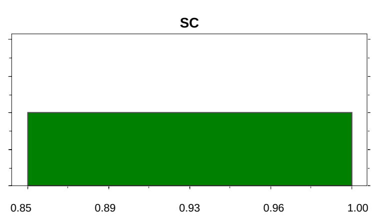

Figure 17: Scaling Factor (SC) Variable Distributions

and opening up of design space could thus be visualized. For instance, if that particular constraint should be relaxed, the effect on the design space could be investigated and assessed quickly.

The coefficients for that RSE were then entered in Crystal Ball and distributions for the variables were chosen, *Figure 14* through *17*. Together with the ranges previously determined in the RSE generation, the Monte Carlo Simulation with 10,000 runs was subsequently executed to allow the designer to decide if the chosen configuration with the given ranges had a chance of achieving a target weight. *Figure 18* and *19* show the design space for variables set at the high level. The figure also showed how the results were distributed. This illustrated that there was a 90% chance that the weight of the airframe was lower then 18,700 lbs., and a 95% chance that it was lower than 19,800 lbs. with these settings for the variables. Alternatively, this meant that 90% or respectively 95% of all possible designs had weights under the respective numbers.

CONCLUSIONS

It was illustrated how parametric structural models could be used in a more physics-based design process at the conceptual level. The study illustrated a statistical approach to assess the outcome of a design. This showed that 95% of the possible designs, with the specified variable range, had a weight that was lower than 19,800lbs.

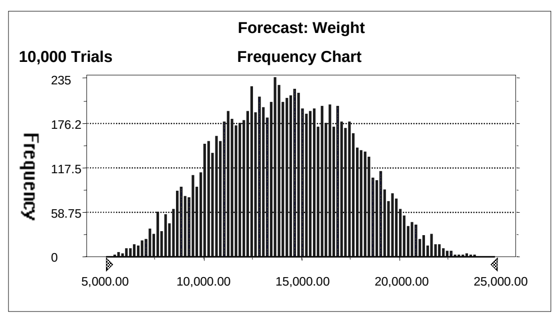

Figure 18: Weight Probability Distribution Function

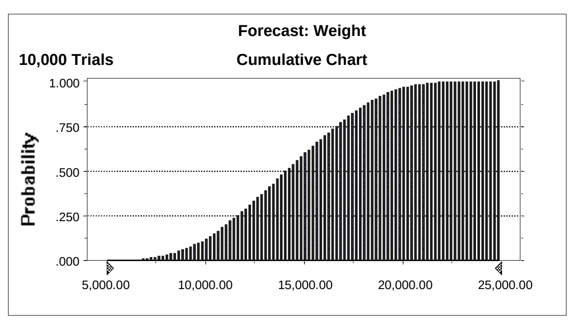

Figure 19: Weight Cumulative Distribution Function

This research has focused on the possibility to generate structural response meta-models for a revolutionary concept with little information available on the hypersonic system. It illustrated how an automated input file generator and an finite element code worked together and made RSEs with minimal effort and input from the designer. This however also showed shortcomings in predicting actual weights.

Further research in the hypersonic vehicle should primarily focus on investigate the effect of aeroelastic constraints and thermal gradients on the weight of the vehicle and the mission requirements. Once this was determined, the effect of technology infusion programs could be assessed using the technology infusion, evaluation and selection methodology (TIES) **[14]**. It nevertheless gave an insight into trends, also invaluable information to the designer.

More importantly however, it should be noted that the capability and fidelity to make weight estimation using FE codes should be improved either by improving the model accuracy or either by new tools proposed by Komarov and Weisshaar **[13]**.

This work should be regarded as a first step in order to illustrate an approach for physics-based modeling and probabilistic feasibility assessment of revolutionary concepts in the domain of hypersonics.

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REFERENCES

1. Graham, M. and Mavris, D. N., "Implementation of Parametric Analysis to the Aerodynamic Design of a Hypersonic Strike Fighter," Presented at 5th AIAA/SAE World Aviation Congress, San Diego, CA, October 10-12, 2000. AIAA-2000-01-5561.

2. Hollingsworth, P. and Mavris, D. N., "A Method for Concept Exploration, Design, and Selection of Hypersonic Vehicles," Presented at 5th AIAA/SAE World Aviation Congress, San Diego, CA, October 10-12, 2000. AIAA-2000-01-5560.

3. McDonald, R. A. and Mavris, D. N., "Formulation, Realization, and Demonstration of a Process to Generate Aerodynamic Meta-Models for Hypersonic Cruise Vehicle Design," Presented at 5th AIAA/SAE World Aviation Congress, San Diego, CA, October 10-12, 2000. AIAA-2000-01-5559.

4. Neill, D. J. and Herendeen, D. J., "ASTROS Enhancements, Volume I – ASTROS User`s Manual," Wright Laboratory, Flight Dynamics Directorate, WL-TR-93-3025, March 1993.

5. Box, G. E. P. and Hunter, W. G., Statistics for Experimenters, An Introduction to Design, Analysis, and Model Building, John Wiley.

6. Giles, G. L., *ELAPS User's Manual*, February 1997.

7. Mavris, D. N. and Hayden, W. T., "Probabilistic Analysis of an HSCT Modeled with an Equivalent Laminated Plate Wing," 1997 World Aviation Congress, Anaheim, CA, October 13-16, 1997. AIAA-97-5571.

8. Hayden, W. T. and Mavris, D. N., "Formulation of an IPPD Methodology for the Design of a Supersonic Business Jet," 1st AIAA/SAE World Aviation Congress, Los Angeles, CA, October 22-24, 1996. AIAA-965591.

9. SAS Institute Inc., *JMP, Computer Program and Users Manual*, Cary, NC, 1994.

10. Decisioneering, Inc., *Crystal Ball, Computer Program and Users Guide*, Denver, Co., 1993.

11. AIAA Foundation, 1999/2000 AIAA Foundation Graduate Team Aircraft Design Competition: RFP for a Hypersonic Strike Fighter, Issued by AIAA September 1999.

12. Raymer, D. P., "Aircraft Design: A Conceptual Approach," AIAA Education Series, 1999, Third Edition.

13. Komarov, V. A. and Weisshaar, T. A., "Aircraft Structural Design – Improving Conceptual Design Level Fidelity," AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, 7th, St. Louis, MO, Sept. 2-4, 1998. AIAA-98-4885.

14. Kirby, M. R. and D. N. Mavris, "Forecasting Technology Uncertainty in Preliminary Aircraft Design," 4th World Aviation Congress and Exposition, San Francisco, CA, October 19-21, 1999. SAE paper no. 1999-01-5631.

15. Hollingsworth, P., De Baets, P. W. G., Egea, I., Graham, M., Hwangbo, C., Liu, B., Lu, Z., McDonald, R. A., Ross, B., and Willing, S., “Peregrine Hypersonic Strike Fighter Weapons System,” Submitted to AIAA June 2000.